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Charm production in the semi-hard approach of QCD and the unintegrated gluon distribution

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Abstract: In the framework of semi-hard QCD approach, we present a consistent analysis of D^* meson production at HERA energies. The consideration is based on universal unintegrated gluon densities, which have BFKL behavior in the small x region. Predictions of the CCFM evolution equation for D^* production are obtained and show a good description of D^* data at HERA.

1 Introduction

The standard parton model is based on the DGLAP [1–4] evolution equations, which re-sums contributions from $[\alpha_s \ln(\mu^2/\Lambda^2)]$. It represents an one-dimensional phase space approximation for the parton motion, also known as the collinear approximation, which gives the correct behavior of the structure functions at not too small values of x. When x becomes smaller, also contributions from $[\alpha_s \ln(\mu^2/\Lambda^2)\ln(1/x)]$ and $[\alpha_s \ln(1/x)]$ need to be considered. In the so called k_t factorization or semi-hard approach (SHA) [5–8], the transverse momenta of the partons in the evolution from large x at the proton vertex towards small x at the hard interaction vertex are taken into account. This evolution in x has been formulated in terms of the BFKL [9–11] evolution equation. The CCFM [12–15] evolution equation includes coherence effects via angular ordering and it reproduces the BFKL (DGLAP) evolution equation in the small (large) x limits, respectively.

The resummation [5–8] of the terms $[\alpha_s \ln(\mu^2/\Lambda^2)]$, $[\alpha_s \ln(\mu^2/\Lambda^2)\ln(1/x)]$ and $[\alpha_s \ln(1/x)]$ in SHA results in the so called unintegrated gluon distribution $\mathcal{F}(x, k_t^2, Q_0^2)$, which determines the probability to find a gluon carrying the longitudinal momentum fraction x and transverse momentum k_t. The factorization scale Q_0^2 (such that $\alpha_s(Q_0^2) < 1$) indicates the non perturbative input distribution. They obey the BFKL [9–11] or CCFM [12–15] equation and reduce to the conventional parton densities $F(x, \mu^2)$ once the k_t dependence is integrated out:

$$\int_0^{\mu^2} \mathcal{F}(x, k_t^2, Q_0^2)\, dk_t^2 = x\, F(x, \mu^2, Q_0^2). \qquad (1)$$

However, in CCFM the unintegrated parton distribution $\mathcal{A}(x, k_t^2, Q_0^2, \bar{q}^2)$ (instead of $\mathcal{F}(x, k_t^2, Q_0^2)$) depends also on the maximum angle for any emission corresponding to $\bar{q}$ (coming from angular ordering). In the small x limit they reduce to $\mathcal{F}$ [15].

To calculate the cross section of a physical process, the unintegrated functions $\mathcal{F}$ or $\mathcal{A}$ have to be convoluted with off-mass shell matrix elements [7,8] corresponding to the relevant partonic subprocesses. In off-mass shell matrix element the virtual gluon polarization tensor is taken in form of SHA prescription [5]:

$$L_{\mu\nu}^{(g)} = \overline{\epsilon_2^{\mu}\epsilon_2^{*\nu}} = p^{\mu}p^{\nu}x^2/|k_t|^2 = k_t^{\mu}k_t^{\nu}/|k_t|^2. \tag{2}$$

The specific properties of semi-hard theory may manifest in several ways. With respect to inclusive production properties, one obtains an additional contribution to the cross sections due to the integration over the k_t^2 region above μ^2 and the broadening of the p_t spectra due to extra transverse momentum of the interacting gluons [5,6,16,17]. It is important that the gluons are not on-mass shell but are characterized by virtual masses proportional to their transverse momentum. This also assumes a modification of the polarization density matrix. A striking consequence of this fact on the J/ψ spin alignment has been demonstrated in [18].

In this paper we present predictions for the production of D^* mesons in photo-production at HERA using the SHA approach. We use an unintegrated gluon density coming from a solution of the CCFM equation (see [19]). We also show predictions based on a parton level Monte Carlo integration using a BFKL-like parameterization of the unintegrated gluon density, and we compare both predictions.

2 Unintegrated gluon distribution and CCFM evolution

The parton evolution at small values of x is believed to be best described by the CCFM evolution equation [12–15], which for $x \to 0$ is equivalent to the BFKL evolution equation [9–11] and for large x reproduces the standard DGLAP equations. The CCFM evolution equation takes coherence effects of the radiated gluons into account via angular ordering. In [19] it is shown that a very good description of the inclusive structure function $F_2(x, Q^2)$ and the production of forward jets in DIS, which are believed to be a prominent signature of small x parton dynamics, can be obtained from the CCFM evolution equation. The main important point there was the treatment of the non-Sudakov form factor, which suppresses radiation at small values of x. In Fig. 1 we show the gluon density obtained from this solution of the CCFM equation [19] as a function of x for different values of k_t^2 at $\bar{q}^2 = 10$ GeV^2. In Fig. 2 we show the gluon density as a function of k_t^2 for different values of x at $\bar{q}^2 = 10$ GeV^2.

For comparison, we also use the results of a BFKL-like parameterization of the unintegrated gluon distribution $\mathcal{F}(x, k_t^2, \mu^2)$, according to the prescription in [20]. The proposed method lies upon a straightforward perturbative solution of the BFKL equation where the collinear gluon density $x\,G(x, \mu^2)$ from the standard GRV set [22] is used as the boundary condition in the integral form (1). Technically, the unintegrated gluon density is calculated as a convolution of collinear gluon density with universal weight factors [20]:

$$\mathcal{F}(x, k_t^2, \mu^2) = \int_x^1 \mathcal{G}(\eta, k_t^2, \mu^2)\,\frac{x}{\eta}\,G(\frac{x}{\eta}, \mu^2)\,d\eta, \tag{3}$$

$$\mathcal{G}(\eta, k_t^2, \mu^2) = \frac{\bar{\alpha}_s}{xk_t^2}\,J_0(2\sqrt{\bar{\alpha}_s \ln(1/\eta)\ln(\mu^2/k_t^2)}), \qquad k_t^2 < \mu^2, \tag{4}$$

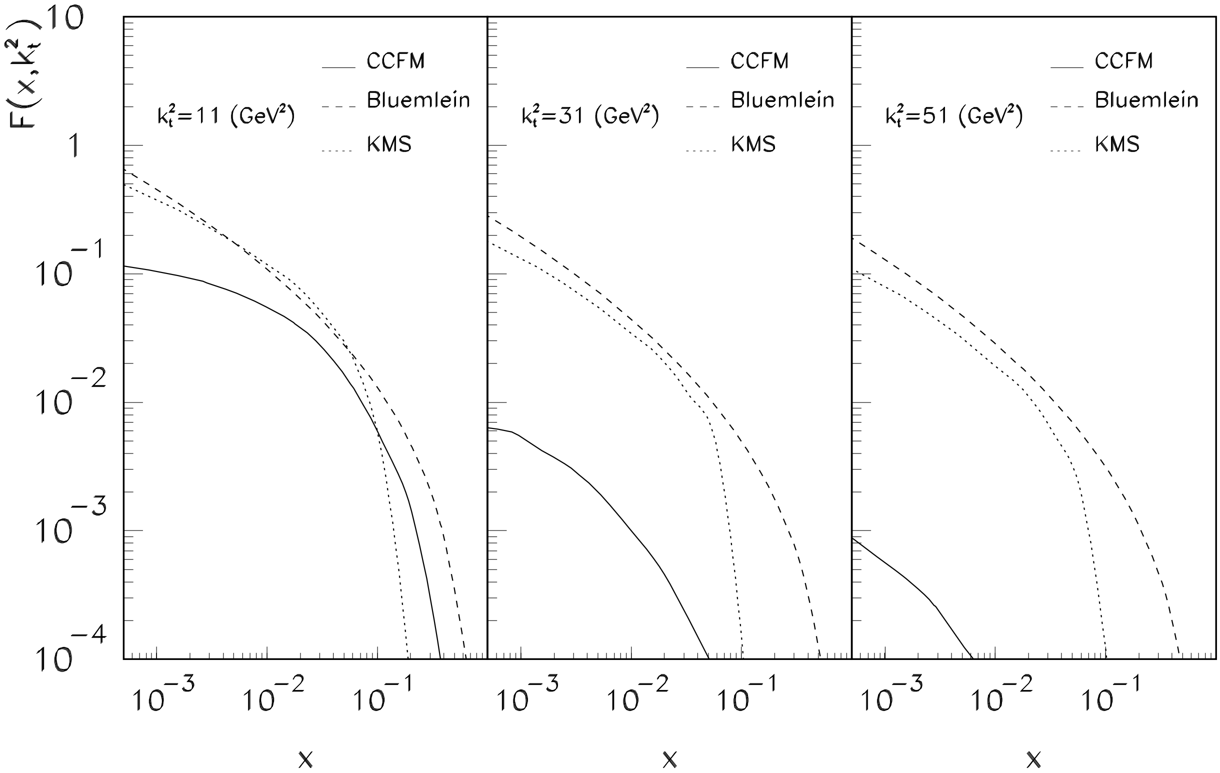

Figure 1: *The gluon density $\mathcal{A}(x, k_t^2, \bar{q}^2)$ (solid line) obtained from a solution of the CCFM equation [19] as a function of x for different values of k_t^2 (at $\bar{q}^2 = 10$ GeV^2). Also shown for comparison is the unintegrated gluon density function $\mathcal{F}(x, k_t^2, \mu^2)$ according to the parameterization of Blümlein [20] (dashed line) at $\mu^2 = 10$ GeV^2 and of Kwiecinski, Martin, Stasto [21] (dotted line).*

$$\mathcal{G}(\eta, k_t^2, \mu^2) = \frac{\bar{\alpha}_s}{x k_t^2} I_0(2\sqrt{\bar{\alpha}_s \ln(1/\eta)\ln(k_t^2/\mu^2)}), \qquad k_t^2 > \mu^2, \tag{5}$$

where J_0 and I_0 stand for Bessel functions (of real and imaginary arguments, respectively), and $\bar{\alpha}_s = 3\alpha_s/\pi$. The latter parameter is connected with the Pomeron trajectory intercept: $\Delta = \bar{\alpha}_s 4\ln 2$ in the LO and $\Delta = \bar{\alpha}_s 4\ln 2 - N\bar{\alpha}_s^2$ in the NLO approximations, respectively, where N is a number [23]. In the following we use $\Delta = 0.35$.

The presence of the two different parameters, μ^2 and k_t^2, in eq.(3) for unintegrated gluon distribution $\mathcal{F}(x, k_t^2, \mu^2)$ refers to the fact that the evolution of parton densities is done in two steps. First the DGLAP scheme is applied to evolve the structure function from Q_0^2 to μ^2 within the collinear approximation. After that eqs.(3)-(5) are used to develop the parton transverse momenta k_t^2. This is in contrast to the CCFM evolution, where the evolution of "longitudinal" and "transverse" components occurs simultaneously.

From Figs. 1 and 2 we see that the BFKL approach gives much harder k_t spectrum than the CCFM approach. However, it has been argued extensively in the literature [21,24,25], that in BFKL a so-called "consistency constraint" should be applied, so simulate at least a part of the large next-to-leading corrections. For comparison we also show in Figs. 1 and 2 the unintegrated gluon distribution from Kwiecinski, Martin, Stasto [21][1]. This shows that the shape of the distributions from BFKL including the "consistency constraint" is similar to

[1]A. Stasto kindly provided us (H.J.) with the program.

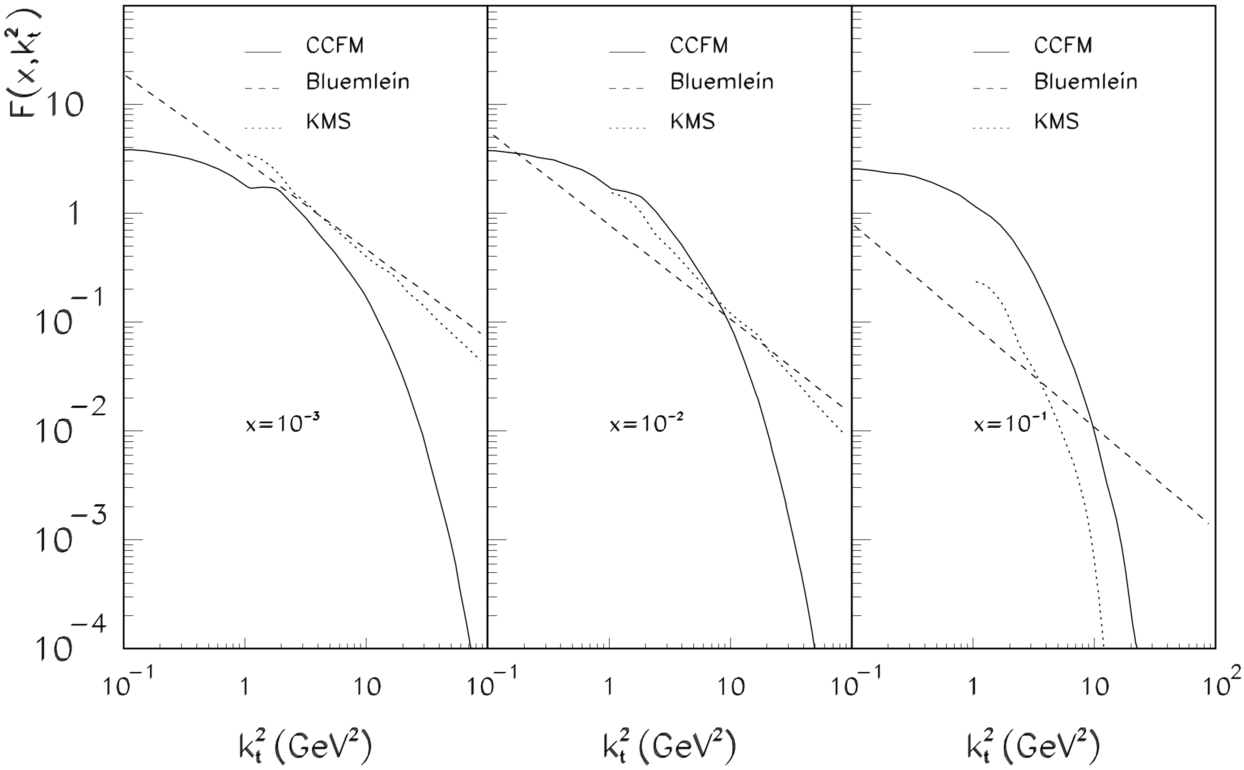

Figure 2: *The gluon density $\mathcal{A}(x, k_t^2, \bar{q}^2)$ (solid line) obtained from a solution of the CCFM equation [19] as a function of k_t^2 for different values of x (at $\bar{q}^2 = 10$ GeV^2). Also shown for comparison is the unintegrated gluon density function $\mathcal{F}(x, k_t^2, \mu^2)$ according to the parameterization of Blümlein [20] (dashed line) at $\mu^2 = 10$ GeV^2 and of Kwiecinski, Martin, Stasto [21] (dotted line).*

the one obtained from CCFM and that the gluon density is stronger suppressed at large k_t as compared to the approach in [20]. Unfortunately we could not use the the gluon distribution from [21], because it started only at $k_t^2 > 1$.

3 Predictions for D^* meson production at HERA

We have used the hadron level Monte Carlo program CASCADE described in [19] to predict the cross section for D^* photo-production at HERA energies. The unintegrated gluon distribution was obtained from the solution of the CCFM equation described in [19]. The scale in α_s was set to k_t^2 in the parton evolution and we used $\Lambda_{QCD}^{(4)} = 0.2$ GeV. For the hard scattering the off-shell matrix element for heavy quarks (including the heavy quark mass with $m_c = 1.5$ GeV) as described in [7] are used together with the one-loop expression for α_s with k_t^2 (of the gluon entering the hard scattering) as the scale. The complete initial state cascade is simulated via a backward evolution as described in [19]. The hadronization was performed by the Lund string fragmentation JETSET [26–28]. The Peterson function with $\epsilon = 0.06$ was used for the charm quark fragmentation.

In Fig. 3 we show the prediction of D^* production as a function of the transverse momentum $p_t^{D^*}$ using the CASCADE Monte Carlo described above and compare it with the measurement of the ZEUS collaboration [30]. We observe a rather good description of the p_t spectrum.

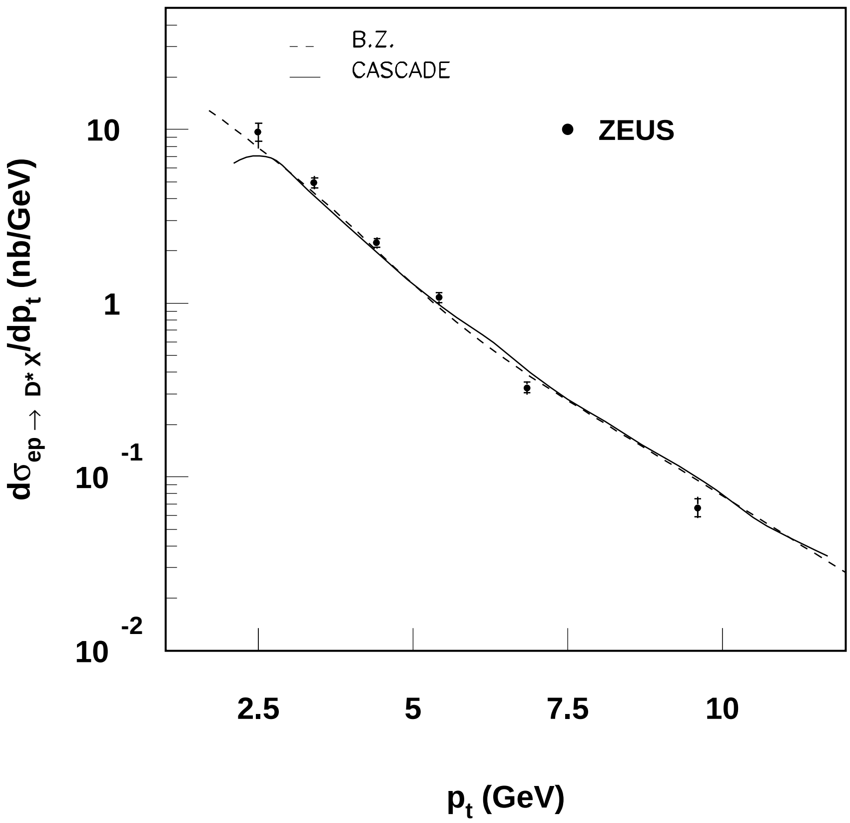

Figure 3: *The differential cross section* $d\sigma/dp_t^{D^*}$ *for* $Q^2 < 1$ GeV^2*. The solid line shows the prediction from the* CASCADE *Monte Carlo and the dashed line is the calculation of [29]. The data point are from [30].*

In Fig. 4 we show the D^* cross section as a function of the pseudo-rapidity η^{D^*} for different regions in p_t. Also here we observe a good description of the experimental data points. Here the main important point is the cross section at values of $\eta^{D^*} > 0.5$.

For comparison we used the results of a calculation of [29] with a parameterization for the unintegrated gluon distribution $\mathcal{F}(x, k_t^2, \mu^2)$, according to the prescription of [20]. Here the scale m_t^2 is used in α_s The results are also shown in Figs. 3 and 4. In general both prediction agree rather nicely. The differences observed are entirely due to the different behavior of the unintegrated gluon distribution as a function of x and k_t^2. In addition in the CCFM approach angular ordering and the maximum angle allowed for any emission plays a important role. The results presented here are similar to the ones obtained from a full NLO calculation. In the SHA approach the gluon entering the hard interaction is off-mass shell, which is a similar situation as in a NLO calculation where the propagators in the 3 parton final states are fully considered. This is in contrast to the LO DGLAP (collinear) case, where the gluon is always treated on-mass shell. However if, in LO DGLAP, heavy flavor excitation is included (via resolved photon processes) then again a similar situation occurs. It was found in [30] that including heavy flavor excitation in LO Monte Carlo programs, lead to better description of the data. The semi-hard approach presented here shows, that a good description of also the photo-production of heavy flavor can be achieved in a theoretically consistent way, without including artificially

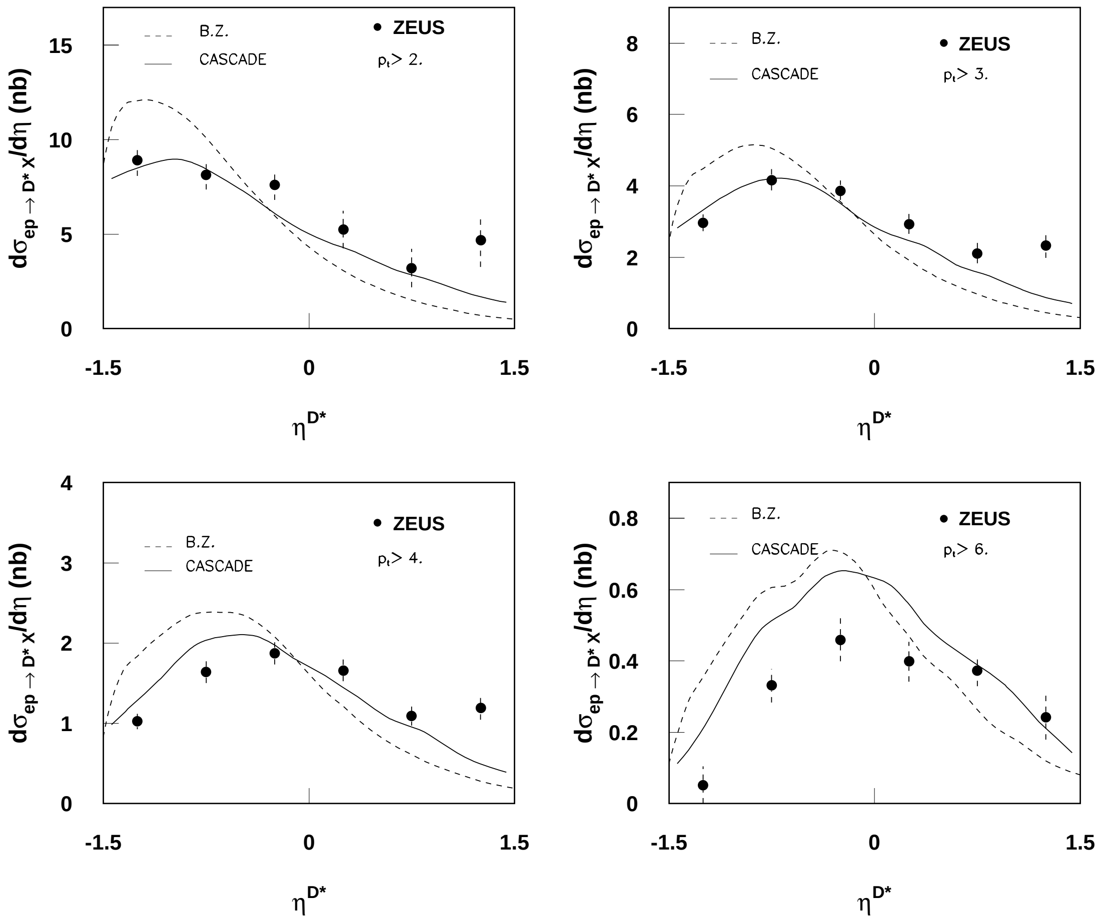

Figure 4: *The differential cross section $d\sigma/d\eta^{D^*}$ for $Q^2 < 1$ GeV^2 for different regions of $p_t^{D^*}$. The solid line show the prediction from the* CASCADE *Monte Carlo and the dashed line is the calculation of [29]. The data point are from [30].*

large intrinsic transverse momenta, or heavy flavor excitation.

4 Conclusions

We have shown that using a unintegrated gluon distribution obtained from a solution of the CCFM evolution equation, that describes the structure function $F_2(x, Q^2)$ and the production of forward jets in DIS at HERA, we can also describe the cross sections of inclusive $D^{*\pm}$ meson production measured at HERA. Within the semi-hard approach the measured cross section as a function of p_t and η_{D^*} can be nicely described. The results are similar to NLO calculations. The shape of the gluon k_t distribution is driven by the BFKL or CCFM evolution equations. This shows that there is no place to include any artificially large intrinsic transverse momentum distribution of parton inside the proton.

It is also interesting to note, that within the semi-hard approach, heavy flavor excitation in the photon is consistently included, by the fact that a gluon radiated close to the quark box can have a transverse momentum larger that of the quarks.

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